1-1-2011

External reinforcement of concrete columns

Muhammad N. S Hadi
University of Wollongong, mhadi@uow.edu.au

FSEXTERNAL REINFORCEMENT OF CONCRETE COLUMNS

Muhammad N S Hadi

ABSTRACT: With the technology development on the compressive strength of concrete over the years, the use of high strength concrete has proved most popular in terms of economy, superior strength, stiffness and durability due to many advantages it could offer. However, strength and ductility are inversely proportional. High strength concrete is a brittle material causing failure to be quite sudden and 'explosive' under loads. It is also known that structural concrete columns concentrically compressed rarely occur in practice. The stress concentrations caused by the eccentric loading further reduce the strength and ductility of high strength concrete. Therefore, studies for high strength concrete columns under eccentric loading are essential for the practical use. A number of high strength concrete columns that are externally reinforced with galvanised steel straps and fibre reinforced polymers subjected to concentric and eccentric loading are experimentally investigated. The experimental results show that external reinforcement can enhance the properties of high strength concrete columns.

INTRODUCTION

Since high strength concrete became a familiar phase in concrete technology in the late 1980s, its application in the construction industry has steadily increased. The wide application has stimulated a number of research studies in many countries including Australia, particularly in the last few years. However, the studies are not enough to predict the behaviour of the material with reasonable accuracy. As a consequence, important issues related to design and construction of high strength concrete structures are not adequately addressed in building codes, therefore, structural designers are unable to take full advantage of the material because of inadequate information.

The increase in brittleness with the increasing strength is of major concern in using high strength concrete. The lack of ductility results in sudden failure without warning, which is a serious drawback. Extensive previous studies have shown that addition of compressive reinforcement and confinement will increase the ductility as well as the strength of material effectively (Razvi and Saatcioglu, 1994; Hadi and Schmidt, 2002). The higher the concrete strength, the more it becomes necessary to provide confinement (Attard and Mendis 1993). Confining the concrete can reduce its brittleness. In the recent years, considerable attention has been focused on the external reinforcement, as one of the methods of confinement, which has been proved by previous studies as an effective method to enhance the structural properties of high strength concrete members (Pessiski, *et al.*, 2001).

Externally reinforcing high strength concrete enhances the properties of concrete columns, most importantly reducing the effect of its brittle behaviour, and allowing the column to attain maximum load carrying capacity. These higher strengths are achieved as a result of the lateral pressures, applied by the external reinforcement of the concrete column. The confinement prevents the lateral expansion of the specimen under axial load, improving the column's stiffness. As a result, the high strength concrete column is able to carry higher loads than if it were unreinforced.

Among the various external reinforcements, steel straps and fibre reinforced polymers are being used. Previous studies have shown that external steel reinforcement increases a column's strength and enables the steel straps to be smaller in size than internal steel reinforcement. As corrosion of the steel straps results in bond deterioration, the steel is galvanised. In recent years, fibre-reinforced polymers wrapping in lieu of steel jacket has become an increasingly popular method for external reinforcement in which fibre reinforced polymers offer improved corrosion and fatigue resistance compared to steel reinforcement (Pantazopoulou, *et al.*, 2001). The high tensile strength and low weight make fibre reinforced polymers ideal for use in the construction industry. Another attractive advantage of fibre reinforced polymers over steel straps as external reinforcement is ease of handling, thus minimal time and labour are required to install them.

This study considers various types of external reinforcement and compares them with experimental results. The effect of the two types of external reinforcing material, galvanised steel straps and fibre

School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia, mhadi@uow.edu.au

reinforced polymers are evaluated. Two sets of tests in terms of eccentric loading and concentric loading are conducted. Then, the effectiveness of the external reinforcement as a confining material under different loading conditions is investigated.

EXPERIMENTAL PROGRAMME

In order to test the performance of concrete columns confined with various reinforcing materials, two sets of tests were designed: five cylindrical concrete columns of 205 mm diameter and 910 mm height were tested under concentric loading. Another set of six cylindrical concrete columns of 205 mm diameter and 920 mm height were tested under eccentric loading with an eccentricity of 50 mm. The configuration of external reinforcement varies for both sets of columns as well. The testing variables selected for this study are: (1) the type of external reinforcement: galvanised steel straps and fibre reinforced polymers (FRP), (2) the number of layers for FRP, (3) the spacing of steel straps, (4) the types of FRP materials and (5) the loading pattern.

In order to have a better insight about the contribution of FRP on confinement and to be able to conduct the theoretical analysis on the behaviour of the column specimens in the main testing program of this study, a preliminary testing on all the reinforcing materials used in this study was conducted as well.

Columns' details

Concentrically loaded columns

Five columns without internal reinforcement were designed for this testing. Each column had a diameter of 205 mm and a height of 910 mm. Four columns continually wrapped with FRP had the following configurations: one-layered and three-layered Carbon fibres, one-layered and three-layered Kevlar Fibres. The remaining plain column was used as a control column. The configuration of this set of columns is summarised in Table 1.

Table 1 - Configuration of the concentrically loaded columns

Column	Diameter (mm)	Height (mm)	Reinforcing Type	Reinforcing Material	Loading Pattern
1	205	910	External		Concentric
2	205	910	External	Single-layered Carbon	Concentric
3	205	910	External	Single-layered Kevlar	Concentric
4	205	910	External	Three-layered Carbon	Concentric
5	205	910	External	Three-layered Kevlar	Concentric

Eccentrically loaded columns

Six concrete columns were cast and tested. Three of the columns were wrapped with three layers of unidirectional fibre reinforced polymers. Two were externally reinforced with galvanised steel straps, each steel strap was 20 mm wide and 0.5 mm thick. Two spacings for the steel straps were used: 10 mm and 20 mm. The final column was internally reinforced with steel helix and longitudinal reinforcement. All the columns were eccentrically loaded until failure with an eccentricity of 50 mm. The testing matrix is summarised in Table 2.

Table 2 - Testing matrix of the eccentrically loaded columns

Column	Diameter (mm)	Height (mm)	Reinforcing Type	Reinforcing Material	Loading Pattern
1	205	920	External	Three-layered Carbon	Eccentric
2	205	920	External	Three-layered E-glass	Eccentric
3	205	920	External	Three-layered Kevlar	Eccentric
4	205	920	External	Galvanised Steel Straps at 10 mm Spacing	Eccentric
5	205	920	External	Galvanised Steel Straps at 20 mm Spacing	Eccentric
6	205	920	Internal	6 N12 Bars and N10 Helix	Eccentric

Eccentric loading

Eccentric loading differs from concentric loading in that it involves concentrating the load a certain distance from the neutral axis of the cross section. As shown in Figure 1, two plates were designed and manufactured in order to apply eccentric loading on the columns. These plates are used on either end of the columns during loading.

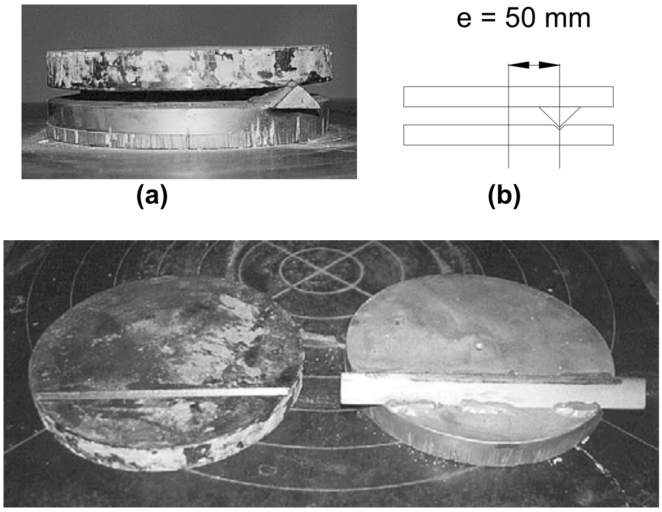

Figure 1 - Steel end plates for eccentric loading

Specimen preparation

Two batches of concrete were used to cast the concentrically and eccentrically loaded columns. The design compressive strength of both batches of concrete was 100 MPa. However, 73.62 MPa and 51 MPa were achieved for the concentrically loaded and eccentrically loaded columns, respectively.

The three types of FRP used in this study were Carbon, Kevlar and E-glass. The epoxy system consisted of two parts, resin and slow hardener, were used to bond the FRP to the surface of the concrete columns. The process of applying the FRP is known as the wet lay up method and was used to wrap all the columns with external FRP confinement.

The band-it method was employed to apply the galvanised straps on the two concrete columns in this study. The galvanised steel straps were placed along the length of column at 20 mm spacing for one column and 10 mm spacing for the second column.

Specimen testing

The testing program consisted of testing the five concrete columns under concentric loading and testing the six cylindrical concrete columns with different external confinement under the eccentric load. The hydraulically operated 5000 kN Denison compression testing machine, located in the Engineering Laboratory at the University of Wollongong was used to test all the columns in this study. All the columns were tested to failure.

OBSERVED BEHAVIOUR AND TEST RESULTS

The failure of the columns in all cases was brittle and in the case of the plain specimen, a very explosive failure. In the case of the FRP confined columns, the snapping of the fibres could be heard throughout the loading as the concrete tried to expand. While for the two galvanised steel straps reinforced columns, failure was sudden and soundless. In each case the straps may have yielded but did not break. This type of failure suggested that the failure of the columns was a direct result of cracking of the concrete by tensile flexure. This type of failure can be explained by the fact that this type of reinforcement may not be suitable for columns under eccentric loading. Table 3 and Table 4 present the testing results of the concentrically loaded and eccentrically loaded columns, respectively.

Table 3 - Testing results for the concentrically loaded columns

Column	Configuration	Ultimate Load (kN)	Axial Deflection (mm)
1	Plain	2 351	5.048
2	Single Layered Carbon	2 860	4.404
3	Single Layered Kevlar	2 490	4.234
4	Three Layered Carbon	2 980	6.514
5	Three Layered Kevlar	2 490	5.574

Table 4 - Testing results for the eccentrically loaded columns

Column	Configuration	Ultimate Load (kN)	Axial Deflection (mm)
1	Three Layered Carbon	840.0	5.20
2	Three Layered E-glass	630.8	4.38
3	Three Layered Kevlar	906.0	5.50
4	Galvanised Steel Straps at 10 mm spacing	720.0	4.22
5	Galvanised Steel Straps at 20 mm Spacing	704.9	3.94
6	Internally Reinforced	636.8	--

The concentrically loaded plain concrete column, as expected, presented a very brittle explosive failure. The column did not experience any excess deflection after reaching the maximum compressive load due to the lack of confinement, which led to the brittle failure.

For the single layered Carbon fibre column under concentric loading, the external confinement provided to this column resulted in a higher ultimate load. However, the failure was still quite explosive and resulted in no increased deflection after reaching the maximum load.

The single layered Kevlar column under concentric loading achieved a slight increase in ultimate load over the plain specimen. And the most promising aspect about this column is that there was a small amount of excess deflection achieved after ultimate load. The failure was less explosive and the column was almost fully confined even after failure.The three layered carbon column under concentric loading achieved significantly better results than the single layered specimen both in strength and deflection. It is of significance to note that the column still appeared to be fully intact after failure. Upon closer inspection, it could be seen that the jacket had a section where the jacket has frayed rather than actually fractured. This meant that even after failure the column still had the ability to withstand load and still maintain its integrity.

The three layered Kevlar specimen under concentric loading also out-performed the single layered specimen, and achieved higher strength and ductility. However, there was not as much excess deflection achieved as the Carbon wrapped specimen. This specimen also remained intact after failure except for the presence of small fractures in the jacket.

This internally reinforced specimen under eccentric loading specimen exhibited a brittle failure under the eccentric loading. The concrete cover started to fall away due to lateral dilation under the loading. However, even after the concrete cover had spalled away, the confined core continued to carry an increasing load. Figure 2 shows the column after failure.

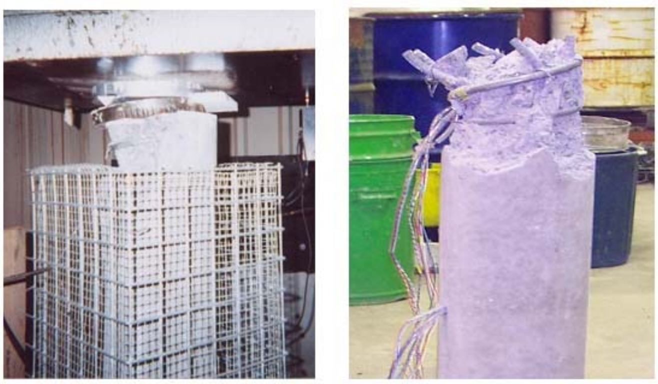

Figure 2 - Failure of the internally reinforced concrete column

The failure of the carbon fibre jacketed concrete columns under eccentric loading was marked by brittle rupture of the hardened fibres at the bottom of the column, which can be seen in Figure 3. Failure was sudden and quite explosive. During various stages of loading, the snapping sounds could be heard, which were attributed to the cracking of the concrete and the stretching of the hardened fibres. The test results show that this column could withstand much higher ultimate load than the internally reinforced column. This finding reveals that carbon could provide significantly greater confining pressure to the high strength concrete column.

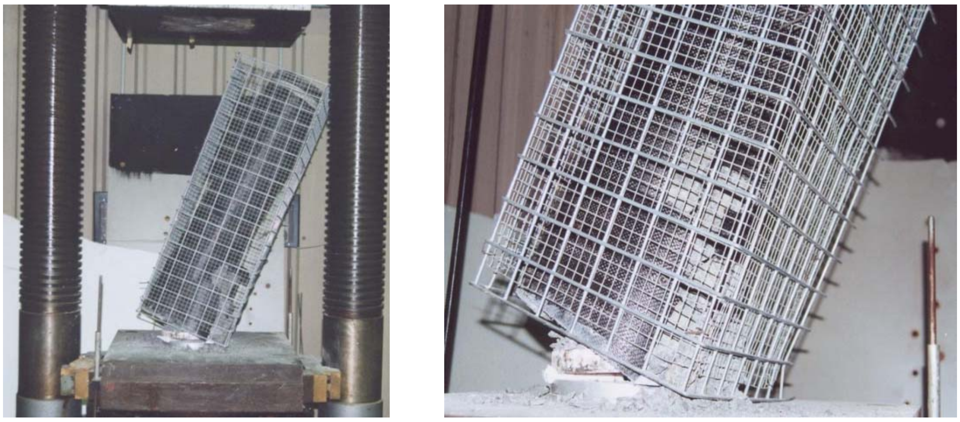

Figure 3 - Failure of the carbon fibres column

For the E-glass wrapped specimen under eccentric loading, the failure of the E-glass wrapped column specimen was marked by fibre rupture at the top of the column. Although it was sudden, the failure could be predicted by the appearance of white patches at the top of the column as the result of the fibre stretching. From Figure 4, it can be seen the layers of E-glass were torn as a result of the eccentric load applied to the column. As the external E-glass confinement tried to prevent the concrete from expansion under loading, it was ruptured when the tensile stress, applied by the concrete lateral expansion, became too large. The results show that the load carrying capacity of this column wrapped with E-glass was slightly lower than the internally reinforced column.

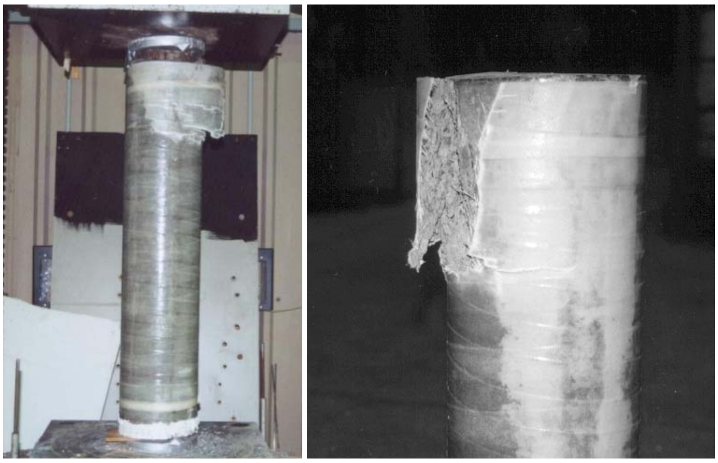

Figure 4 - Failure of the E-glass wrapped column

For the Kevlar wrapped concrete column under eccentric loading, the material used to wrap this column is one sheet of Kevlar 920 mm wide rather than the roll of tape. The failure mode of this column was similar to that of the E-glass specimen; fibres were ruptured at the top end of the column. This can be seen in Figure 5. Cracking of Kevlar fibre could be heard throughout the testing with the failure of the column signified by a loud snap of the Kevlar jacket. The largest load carrying capacity was achieved by this column compared with other eccentrically loaded columns and was due to the external confinement of the continuous sheet. However, the failure was sudden and loud.

For the galvanised steel strapped column at 10 mm spacing under eccentric loading, it was found this column failed in the tensile bending region under eccentric load. Figure 6 shows the failure of this column occurred in the space of two straps. This can be explained as a result of there being no reinforcement in this region. However, the crack was much smaller and failure occurred closer to the bottom of the column when compared to the column with steel straps in 20 mm spacing. The failure was brittle and soundless.

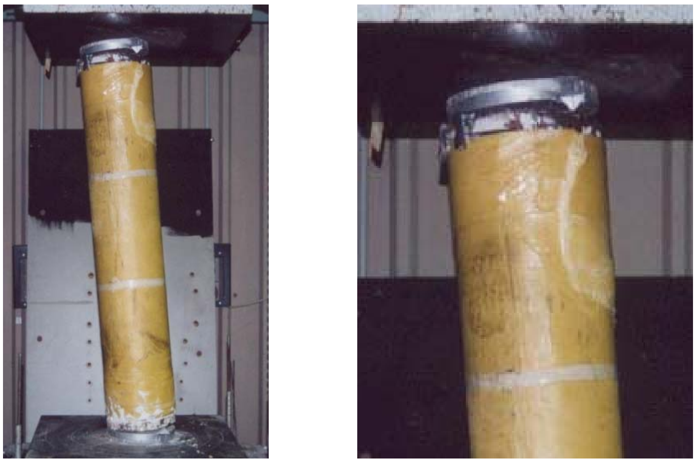

Figure 5 - Failure of the Kevlar wrapped column

Figure 6 - Failure of the steel strapped column with 10 mm spacing

For the galvanised steel straps at 20 mm spacing under eccentric loading, the failure of this column was similar to that of another galvanised steel straps wrapped column, in that the cracking of the concrete on the tension side marked the failure. Also evident in Figure 7, is that failure, again occurred in between the galvanised steel straps and the straps themselves. As the increased spacing of straps resulted in a larger area of the column being un-reinforced, the column failed because of a substantial crack in the concrete. The results shown in Table 4 confirm that the larger the spacing between the straps, results in a lower load carrying capacity.

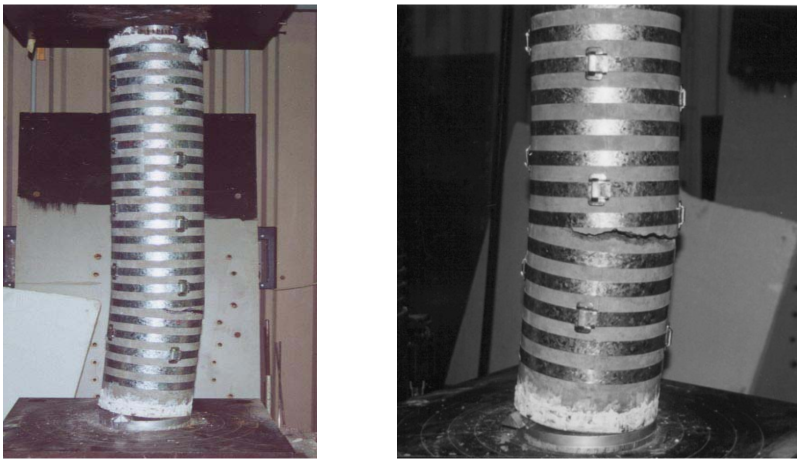

Figure 7 - Failure of the steel strapped column with 20 mm spacing

COMPARISON AND ANALYSIS

From the two sets of experiments conducted in this study, it can be noted that the Carbon wrapped columns outperformed the other types of reinforced columns except the Kevlar sheet wrapped column, which was proved by the testing results of the eccentrically loaded columns. The testing results indicated that Carbon fibres wrapping is more effective for the external confinement compared to the galvanised steel straps and E-glass. However, this is not the case in the Kelvar sheet wrapping column, which presented the largest loading capacity as the continuous sheet was used as the external confinement. Again, this finding proved the layout of fibres has a significant influence on the behaviour of the eccentrically loaded columns.

The comparison of the eccentrically loaded columns shows that all the externally reinforced columns out-performed the internally reinforced column excluding the E-glass specimen, which almost achieved the same strength. The E-glass was confirmed to be the weakest reinforcing material, which presented an ultimate load 10% lower than that of the two Band-It columns and a 44% decrease in compressive load compared to the Kevlar fibre sheet confined column.

Another comparison made between the two galvanised steel straps wrapped columns shows that the larger the spacing between the straps results in a lower load carrying capacity. However, the column with galvanised steel straps at 20 mm spacing exhibited only 2.2% decrease in the loading carrying capacity. Nonetheless, there was a 26% and 16% decrease in ultimate load over the Kevlar fibre sheet and carbon fibre confined columns respectively. And both columns achieved slightly higher ultimate load compared to the internally reinforced column, which proved the external confinement with galvanised steel straps is also more effective than the internal reinforcement. But the failure of the columns with this type of reinforcement is sudden, which indicates that the galvanised steel straps have very little effect on improving the ductility of the columns.

The comparison among the concentrically loading columns confirmed that the confinement significantly enhances the strength, stiffness and ductility of high strength concrete, in particular when applied in multiple layers.

CONCLUSIONS

The work carried out in this study involved two sets of testing: five columns under concentric loading and six columns under eccentric loading, which are mainly set to evaluate the effectiveness of various types of the external reinforcement. The results from both sets of tests allow the following conclusions to be drawn:

- The methods of external reinforcement can be used as an alternative method of reinforcement to enhance the properties of high strength concrete. It has been shown that the confinement of the concrete prevents the concrete from expanding and therefore allows the concrete to absorb higher stresses, resulting in a higher load carrying capacity.
- The tests proved that the benefits of confinement could be enhanced by applying multiple layers, which can be seen from the results of testing the concentric loading columns.
- The test results also indicated that the Carbon fibres provides the greatest amount of confinement, and had significantly better results, if the external confinement was achieved by the application of FRP in roll of tape.
- The highest load carrying capacity achieved by Kevlar sheet wrapped column confirms that the wider rolls of the fibre reinforcement can provide a greater confining stress. This also can be concluded that the fibre layout has significant influence on the behaviour of concrete structural members.
- The external confinement with galvanised steel straps improves the strength of the column to a certain extent. The brittle, sudden, soundless failure of the galvanised steel straps wrapped columns shows that the galvanised steel straps had very little effect on improving the ductility of the columns.
- E-glass proved to be the weakest reinforcing material in this study. The ultimate load achieved by the E-glass wrapped specimen was even lower than that for the internally reinforced column.

REFERENCES

Attard, M M and Mendis, P A, 1993. Ductility of high strength columns, *Australian Civil Engineering Transactions*, 35(4), pp 295-306.

Hadi, MNS and Schmidt, L C, 2002. Use of helices in reinforced concrete beams. *ACI Structural Journal*, 99(2), pp 191-198.

Pantazopoulou, S J, Bonacci, J F, Thomas, M D A and Hearn, 2001. Repair of corrosion-damaged columns with FRP wraps, *Journal of Composites for Construction*, 5, February, pp 3-11.

Pessiki, S, Harries, K A, Kestner, J T, Sause, R and Ricles M J, 2001. Axial behaviour of reinforced concrete columns confined with FRP jackets, *Journal of Composites for Construction, 5, November*, pp 237-245.

Razvi, S R and Saatcioglu, M, 1994. Strength and deformability of confined high-strength concrete column, *ACI Structural Journal*, 91, November-December, pp 678-687.